High Resolution Computational Unsteady Aerodynamic Techniques Applied to Maneuvering Unmanned Combat Aircraft

Presenter
Maj Scott Morton
USAF Academy

Collaborators
Maj Jim Forsythe, Prof Russ Cummings ***USAF Academy***
Prof Kyle Squires ***Arizona State University***
Ken Wurtzler, Bill Strang, Bob Tomaro ***Cobalt Solutions, LLC***
Philippe Spalart ***Boeing Commercial Airplanes***

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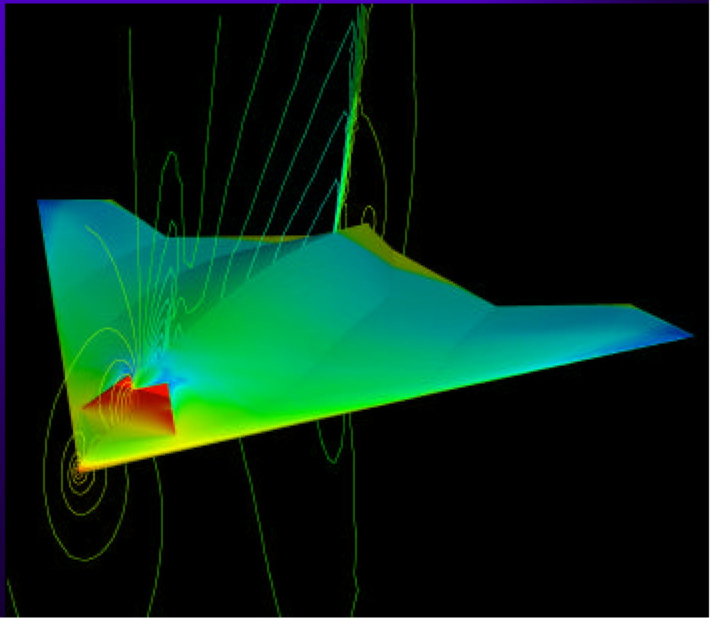
Outline

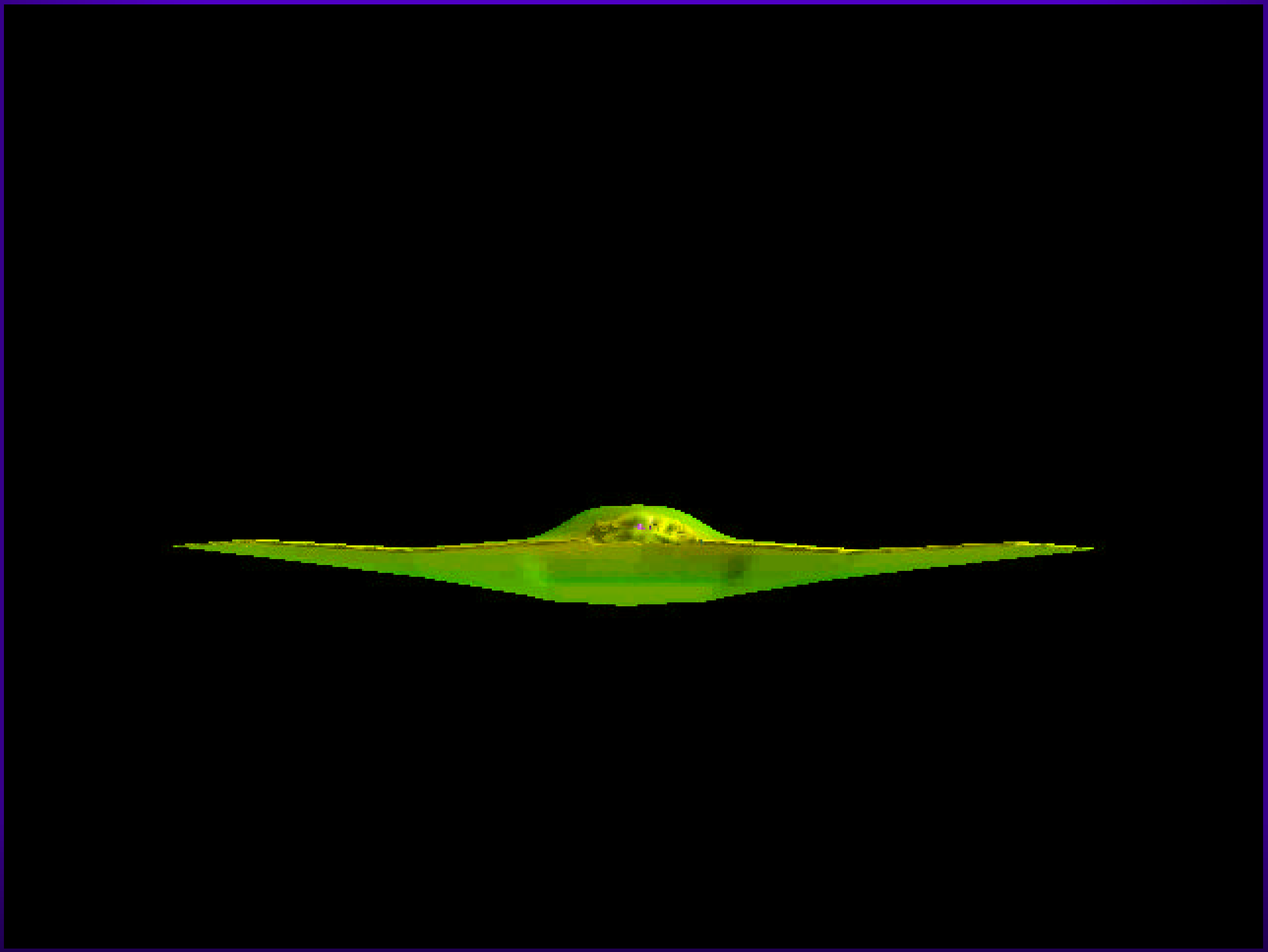
- Overview and motivation
  - UCAV Simulation Issues
  - Simulation hierarchies
- Static Case Validation of DES
- Forced Motion Validation of DES
- Embedded LES Modifications to DES
- Future Areas of Research Necessary
- Conclusions

UCAV Simulation Issues

- Unmanned Combat Air Vehicles are capable of super-maneuverability
- Main Challenges
  - Maneuvers occur at high Reynolds numbers for which the underlying fluid motion is usually turbulent
  - Incorporates massively separated flows and complicated vortical flows
  - Complete simulation requires solid-body motion, 6-DOF, and aeroelasticity
- Wind tunnel tests problematic
  - Important Reynolds number effects
  - Motion mechanical systems intrusive
- Flight tests costly, time-consuming
- Computational modeling an important element for advancing fundamental understanding and engineering prediction



Unmanned Combat Air Vehicles (UCAV)



Simulation provided by Mr Ken Wurtzler, Cobalt Solutions LLC

Massive Separations/Vortical Flowfields

- ***Challenges and issues***
  - **flow fields are inherently unsteady, chaotic, and three-dimensional**
    - » **accuracy is crucial at high angle of attack: lift, drag, and moments**
    - » **complex nature of massive separation/vortical flowfields**
      - **defeats conventional turbulence models**
      - **higher fidelity computational techniques required**
  - **flow fields are described by the Navier-Stokes equations**
    - » **analytical solution for aircraft not possible**

Choice of the computational model

increase in cost

- **Direct Numerical Simulation (DNS)**
  - **solution of the Navier-Stokes equations without use of an explicit turbulence – limited to low Reynolds numbers**
  - **powerful research tool**
  - ***ready for full aircraft in ~2080***
- **Large Eddy Simulation (LES)**
  - **direct resolution of the large, energy-containing scales of the turbulent flow, model only the small eddies**
  - **high computational cost in boundary layers**
  - ***ready for full aircraft in ~2045***
- **Reynolds-average Navier-Stokes (RANS)**
  - **model the entire spectrum of turbulent motions**
  - **Highly unreliable performance in separated flows**
  - ***ready for full aircraft today***

increase in empiricism

DES method combines RANS and LES

Detached-Eddy Simulation (DES)

- Turbulence modeling approach proposed by Spalart *et al.* (1997)
  - Combines **Large Eddy Simulation,** and **Reynolds-Averaged** approaches
  - Designed to provide **accurate solutions for massively separated flows**
  - Can resolve **unsteady flow features**
    - » Aero-acoustics, aero-elasticity
  - RANS model responsible for **predicting BL growth and separation (NUMERICALLY FEASIBLE)**
  - **LES** model responsible for **prediction of unsteady flow in separated region (ACCURATE)**

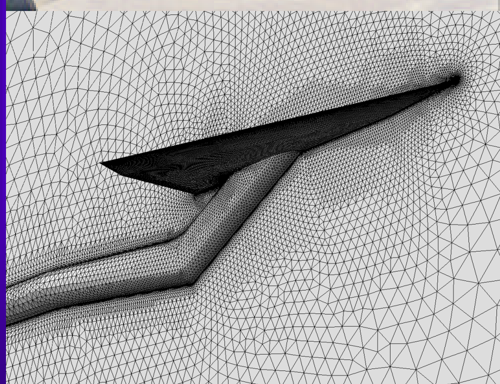
Flow Solver – Cobalt

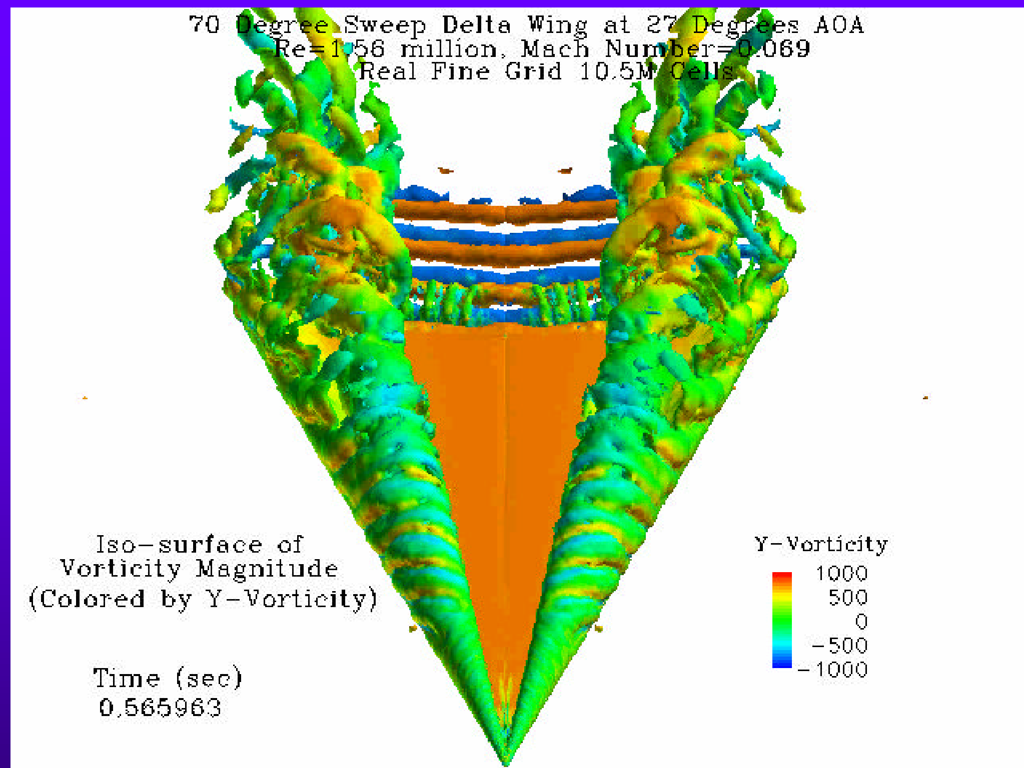
- CHSSI Developed
- Hybrid-Unstructured, Compressible Solver
- Spatial Operator
  - Riemann Solver
  - Least Squares Gradients
  - TVD limiting
  - Second order accurate
- Temporal integration
  - Point-implicit
  - Newton sub-iteration
  - Second order accurate
- Parallel Performance
  - Domain decomposition using ParMETIS
  - MPI
  - Over 98% efficient on 1024 processors

Static Case Validation of Detached Eddy Simulation

Delta Wing Vortex Breakdown

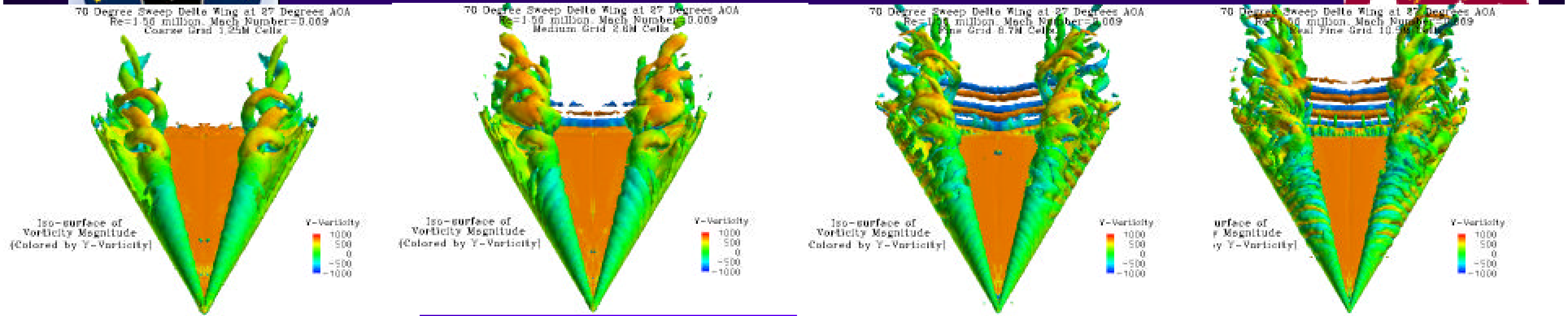
Photo Courtesy of NASA

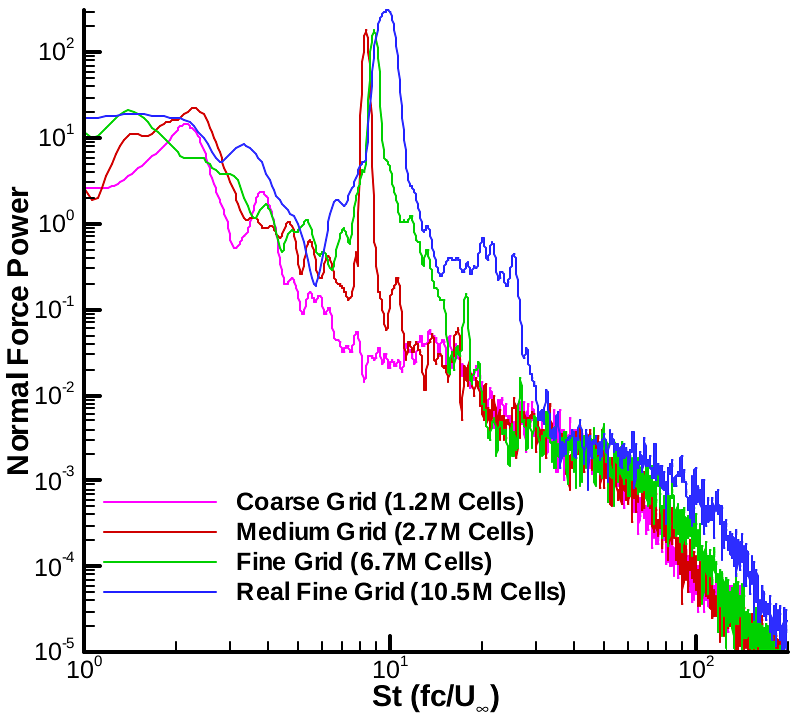


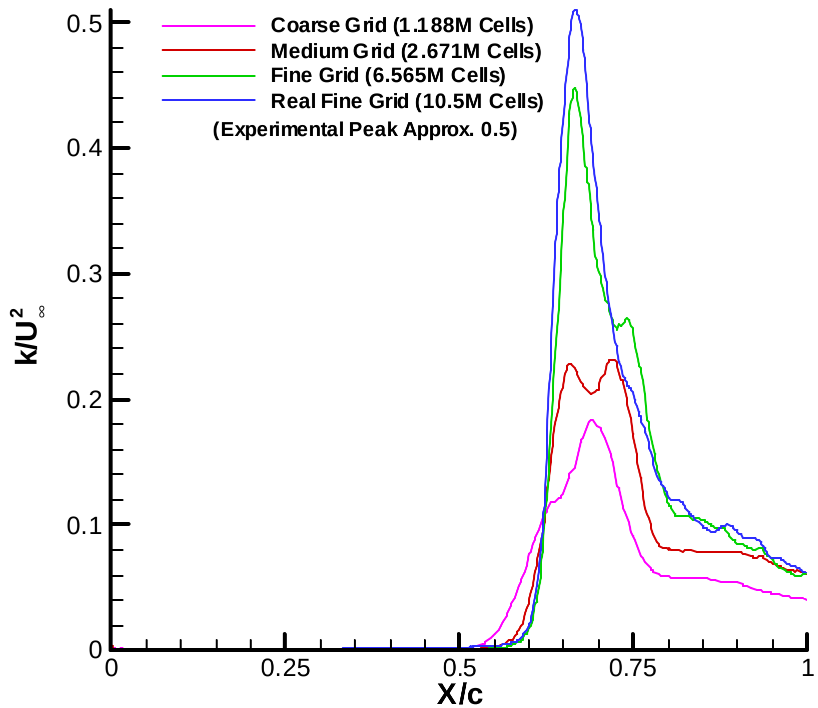


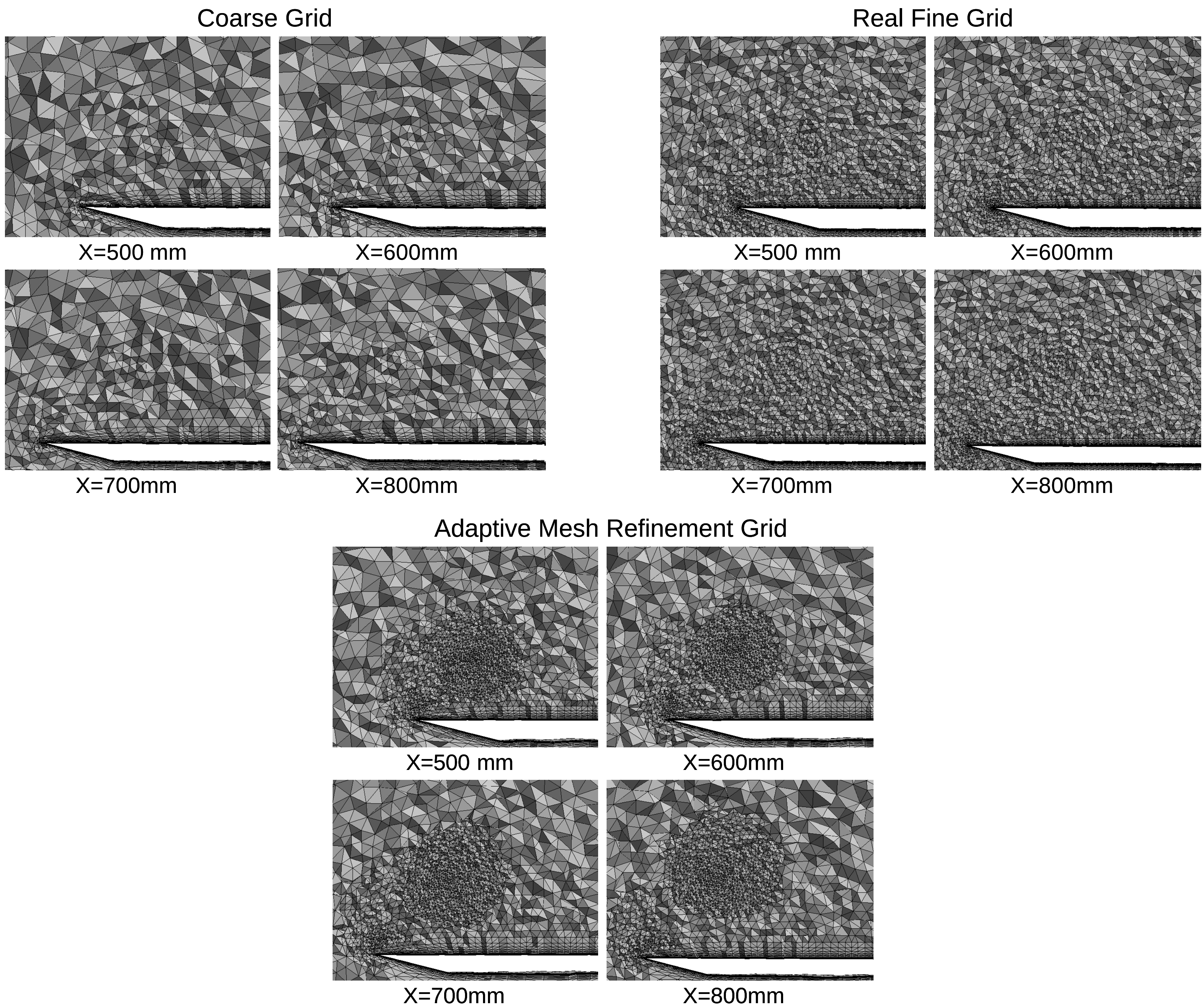
- Scott Morton (PI), Jim Forsythe, Tony Mitchell
- AFOSR project: Aeroelasticity predictions (PM: Tom Beutner, John Schmisseur)
- AIAA 02-0587

Grid Sensitivity Study

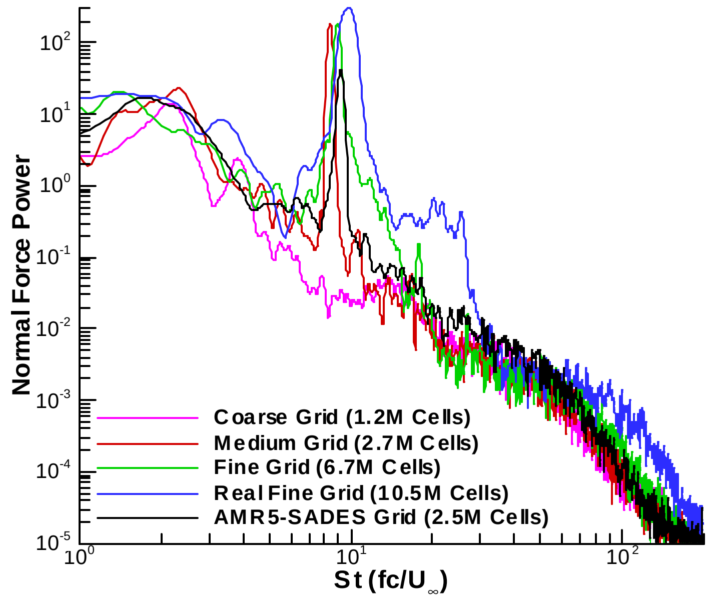


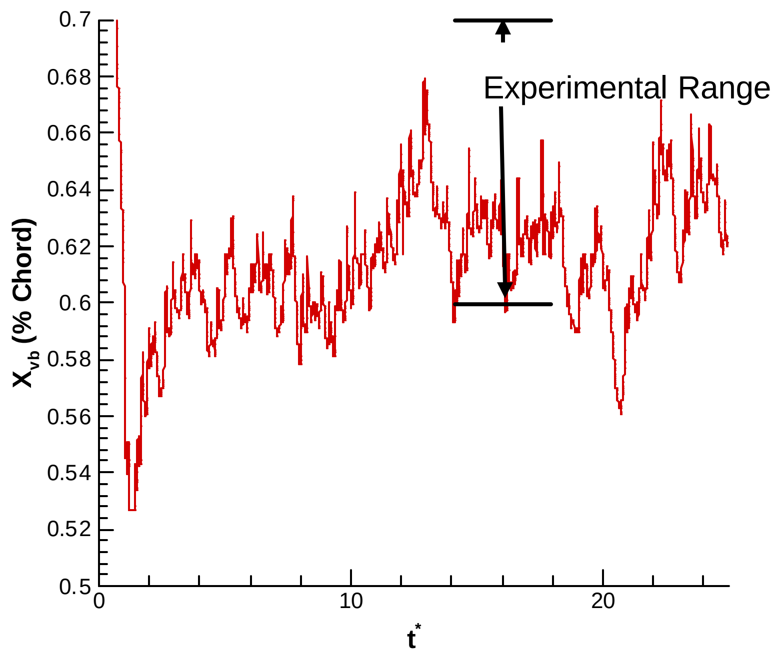


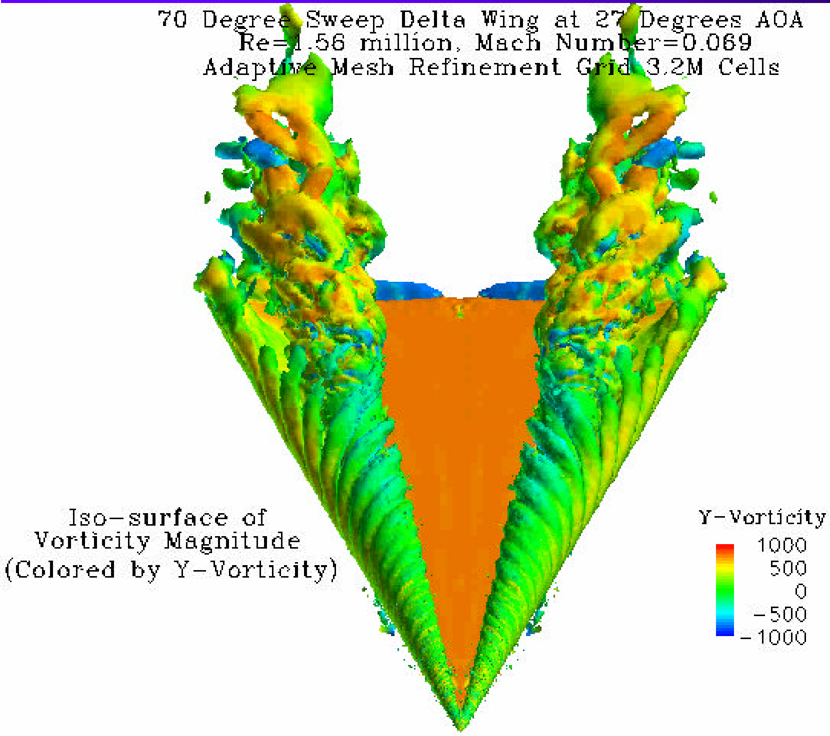



Coarse Grid
X=500 mm
X=600mm
X=700mm
X=800mm
Real Fine Grid
X=500 mm
X=600mm
X=700mm
X=800mm
Adaptive Mesh Refinement Grid
X=500 mm
X=600mm
X=700mm
X=800mm

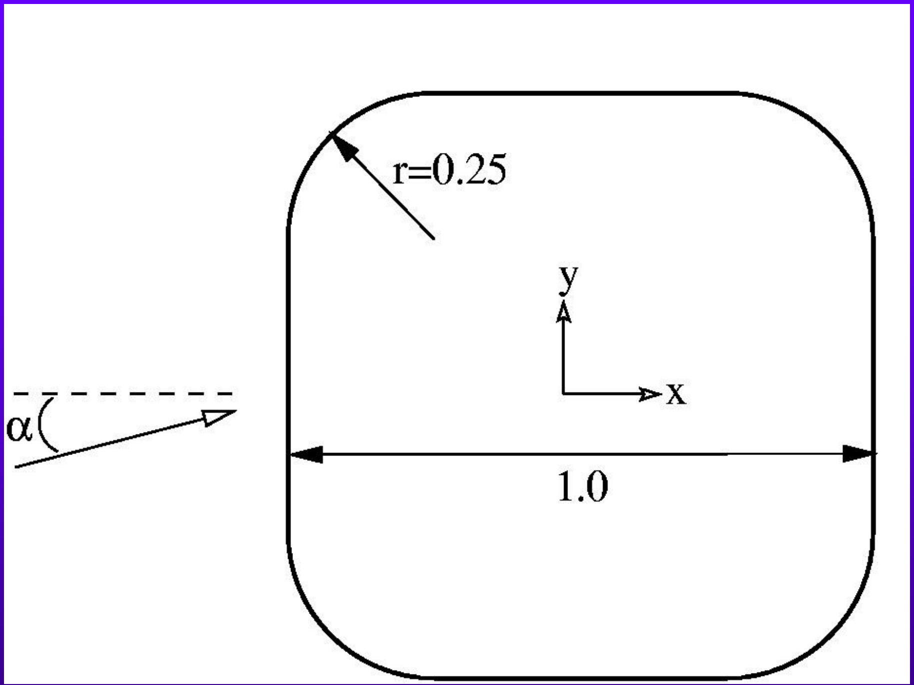
Normal Force Power Spectral Density Analysis







2D Square with Rounded Corners



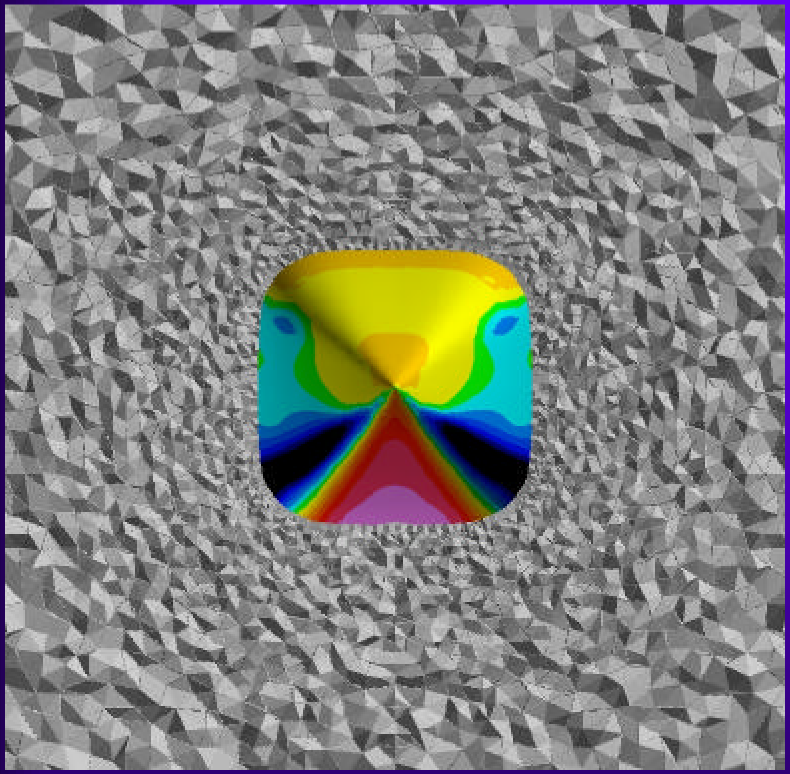
- **Data of Polhamus**
- **Re=800,000**
- **a=10°**
- **Computations made on structured and unstructured grids of various domain sizes and grid spacing**

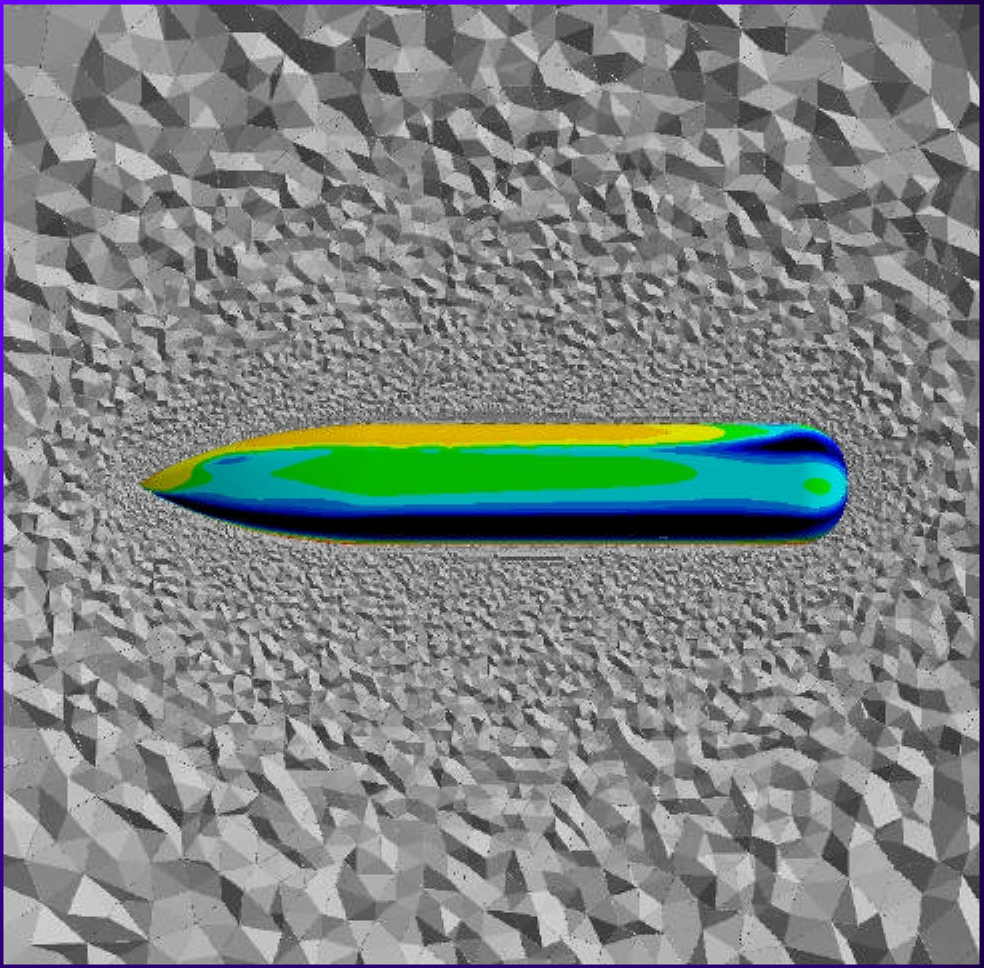
❖ **Kyle Squires (PI), Jim Forsythe, Philippe Spalart**

❖ **AFOSR project: Spin prediction (PM: Tom Beutner)**

❖ **DNS/LES IV, ERCOFTAC Vol 8**

Rectangular Ogive - 90°





rounded-square cross section

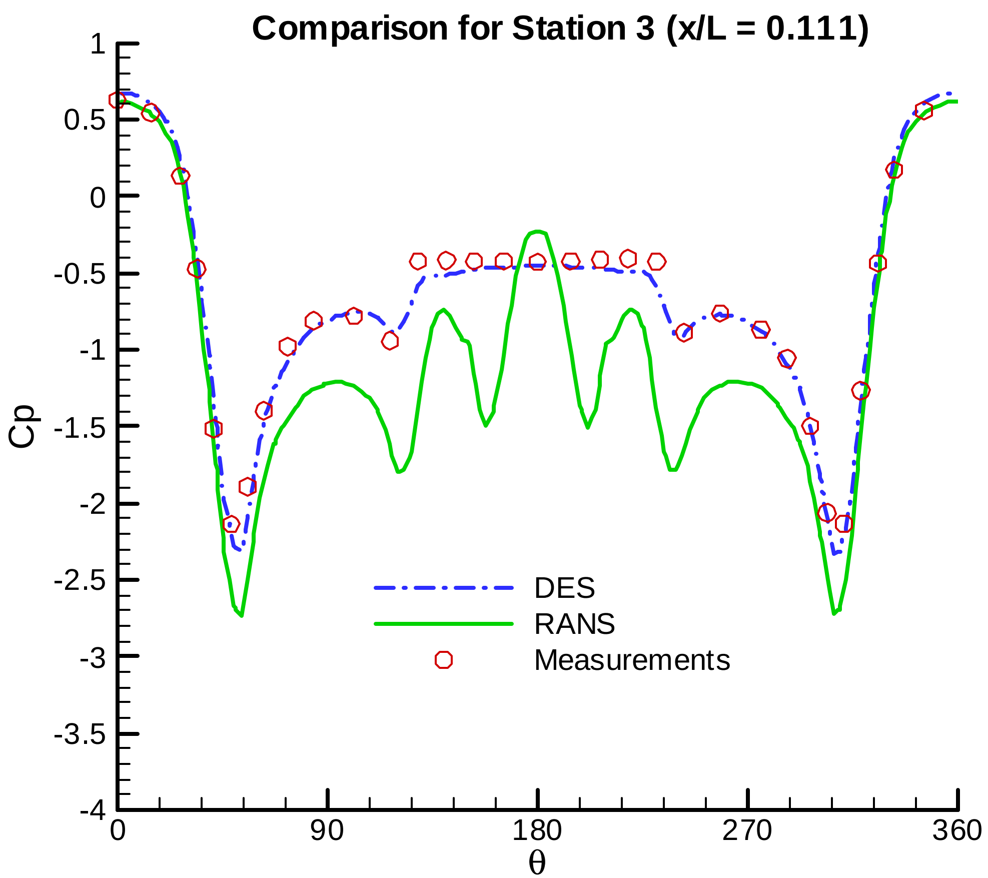
corner radius is 1/4 of the diameter

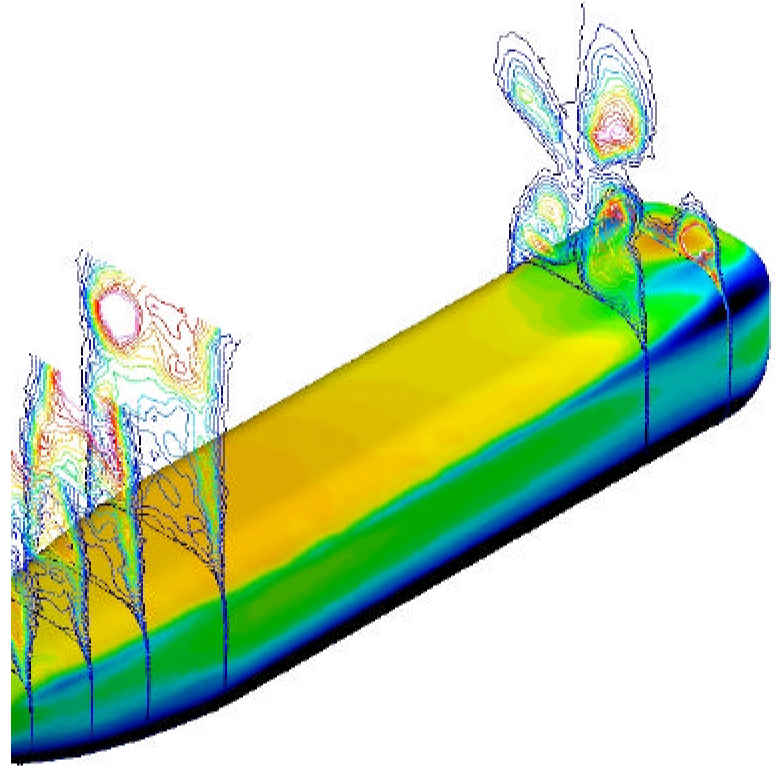
6:1 rectangular ogive

main section 3.5b

endcap 0.5b

Planar Cuts of Eddy Viscosity





DES

pressure

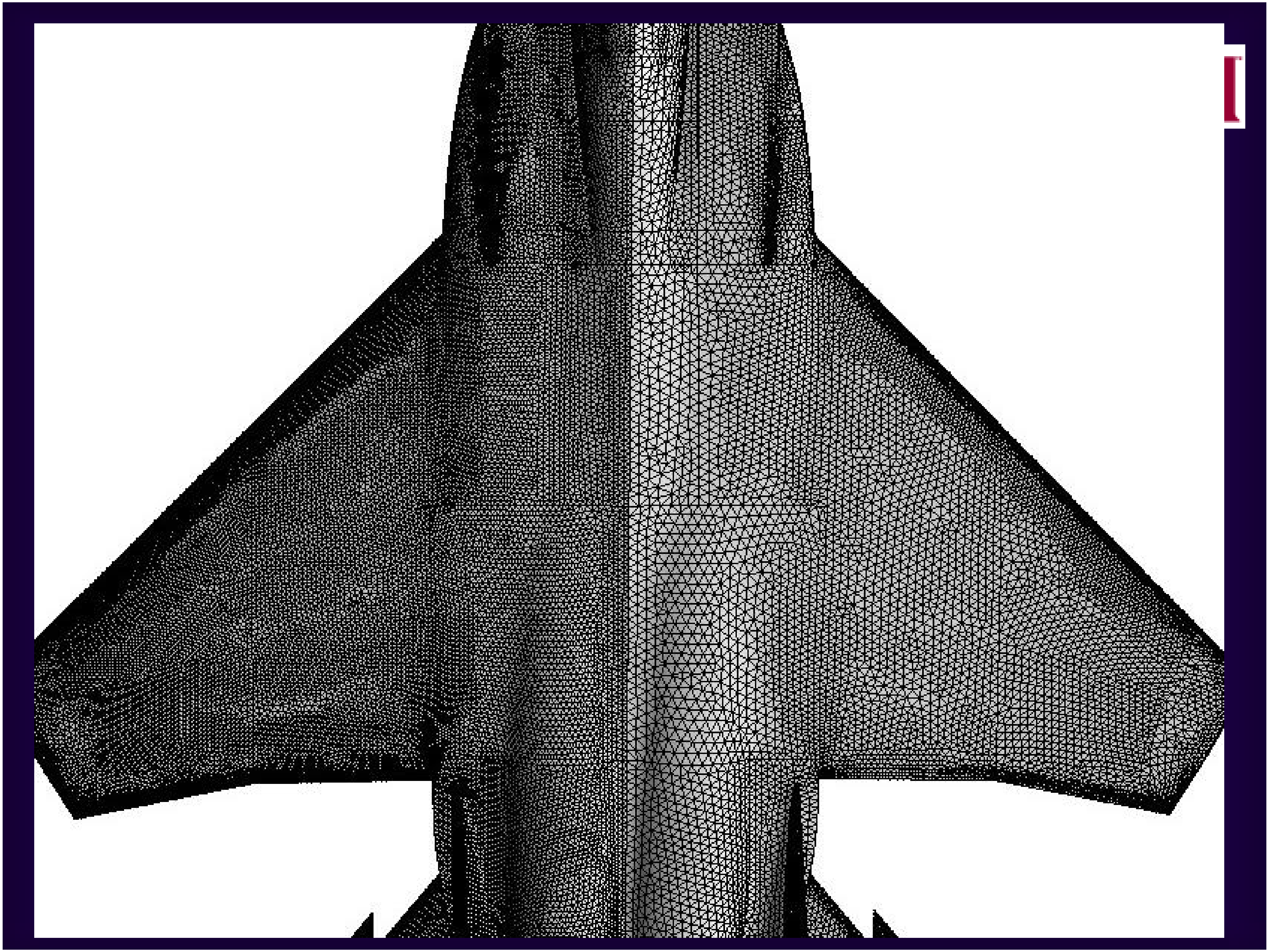
F-15E at 65° alpha

- Grid consists of 5.9M cells (half aircraft)
  - Prisms in the boundary layer (using blacksmith)
    - » Conversions to prisms saved 2M cells
  - Tetrahedrons elsewhere
  - Average first $y^+=0.7$
  - One man-week to create
  - $Re=13.6x10^6$
- 2 days to compute 10,000 iterations on 256 processors (*tempest - MHPCC*)
- Time step and grid sensitivity examined

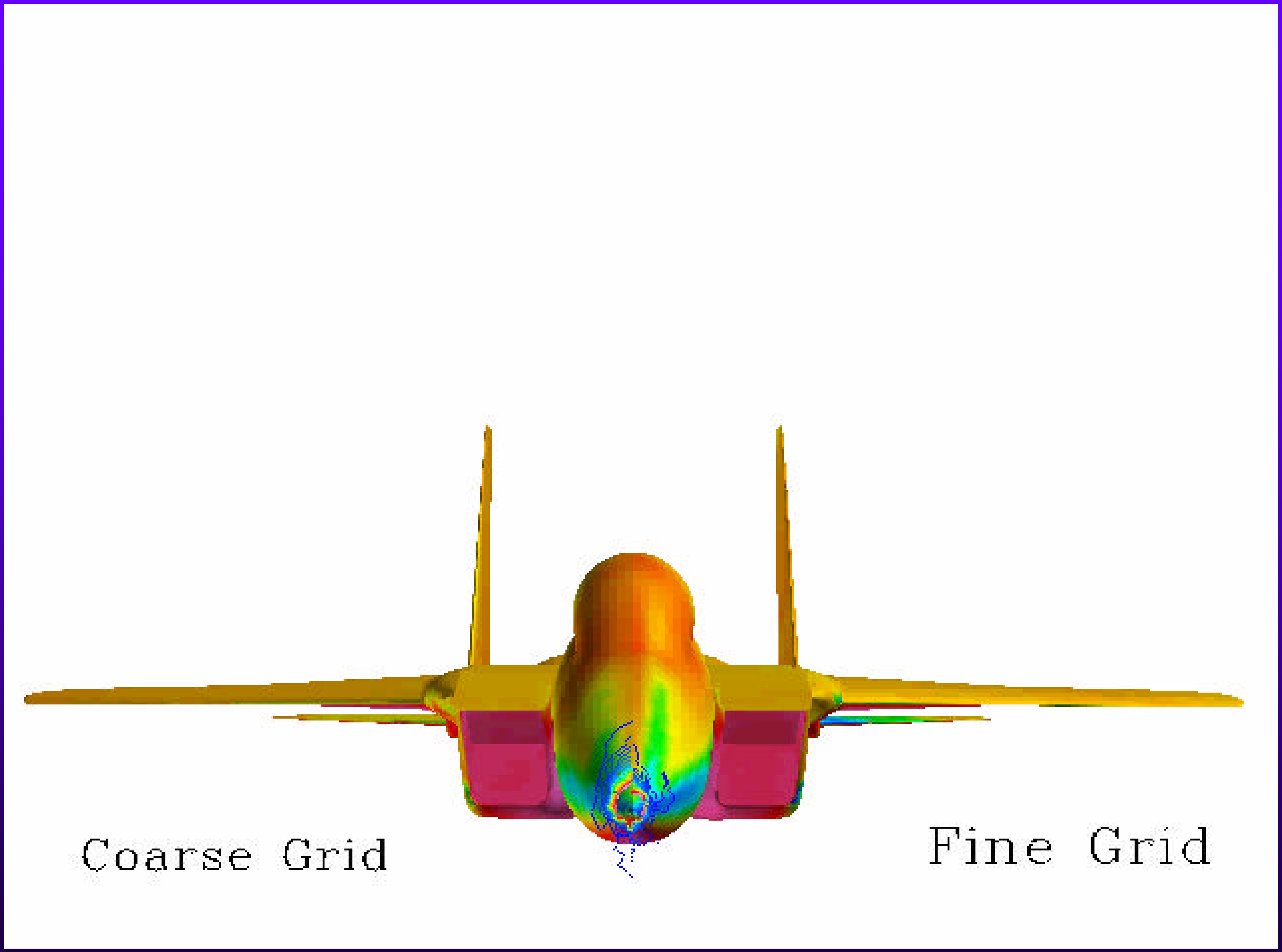
❖ Jim Forsythe (PI), Kyle Squires, Ken Wurtzler, Philippe Spalart

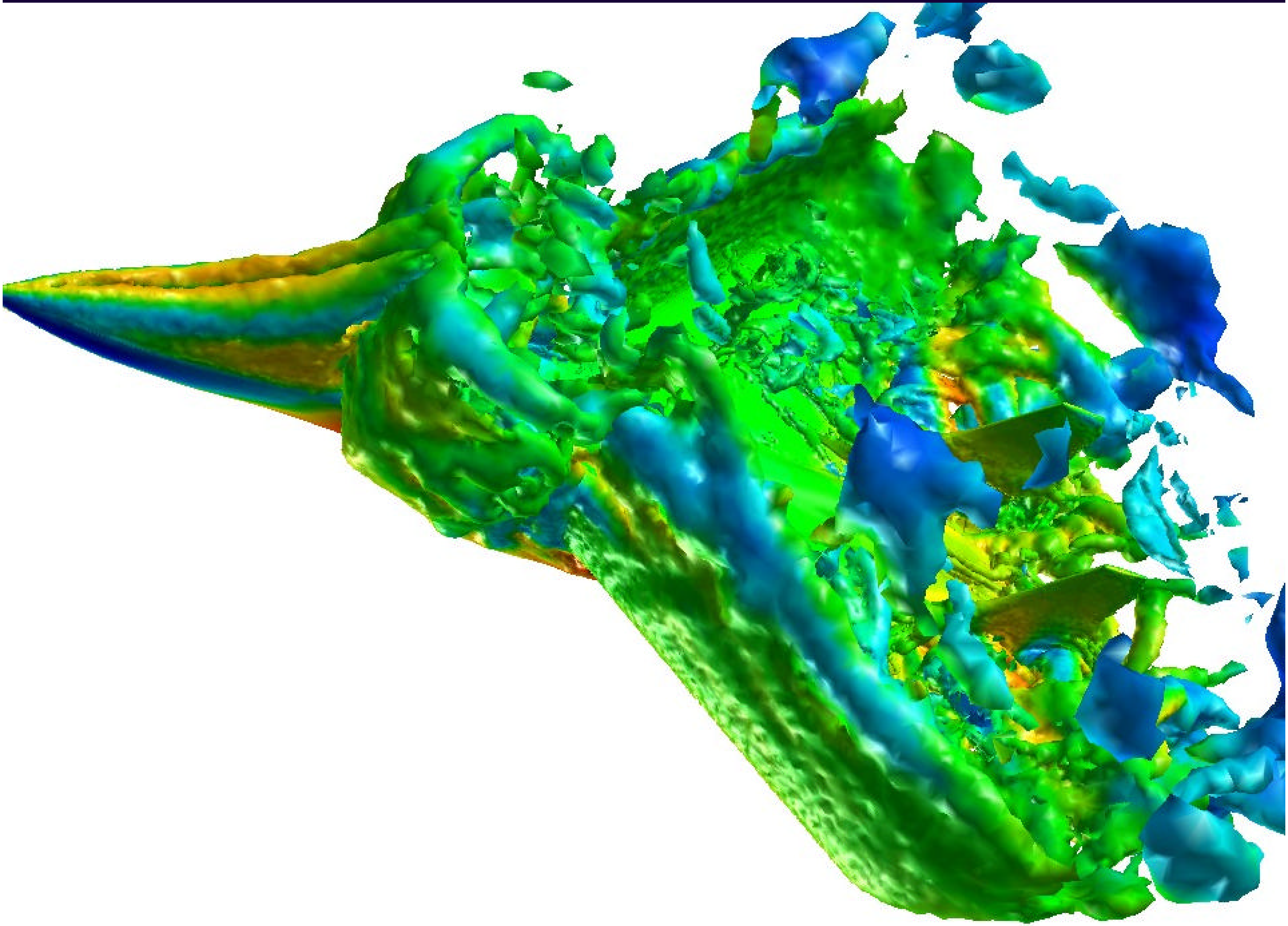
❖ AFOSR project: Spin prediction (PM: Tom Beutner)

❖ AIAA 02-0591

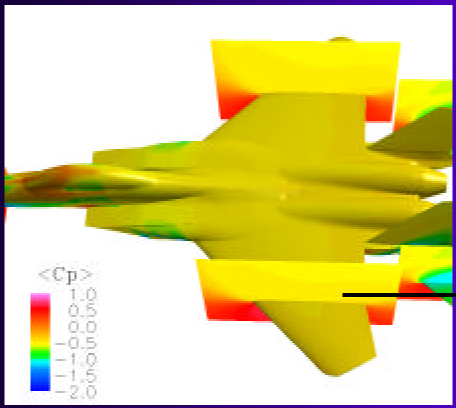


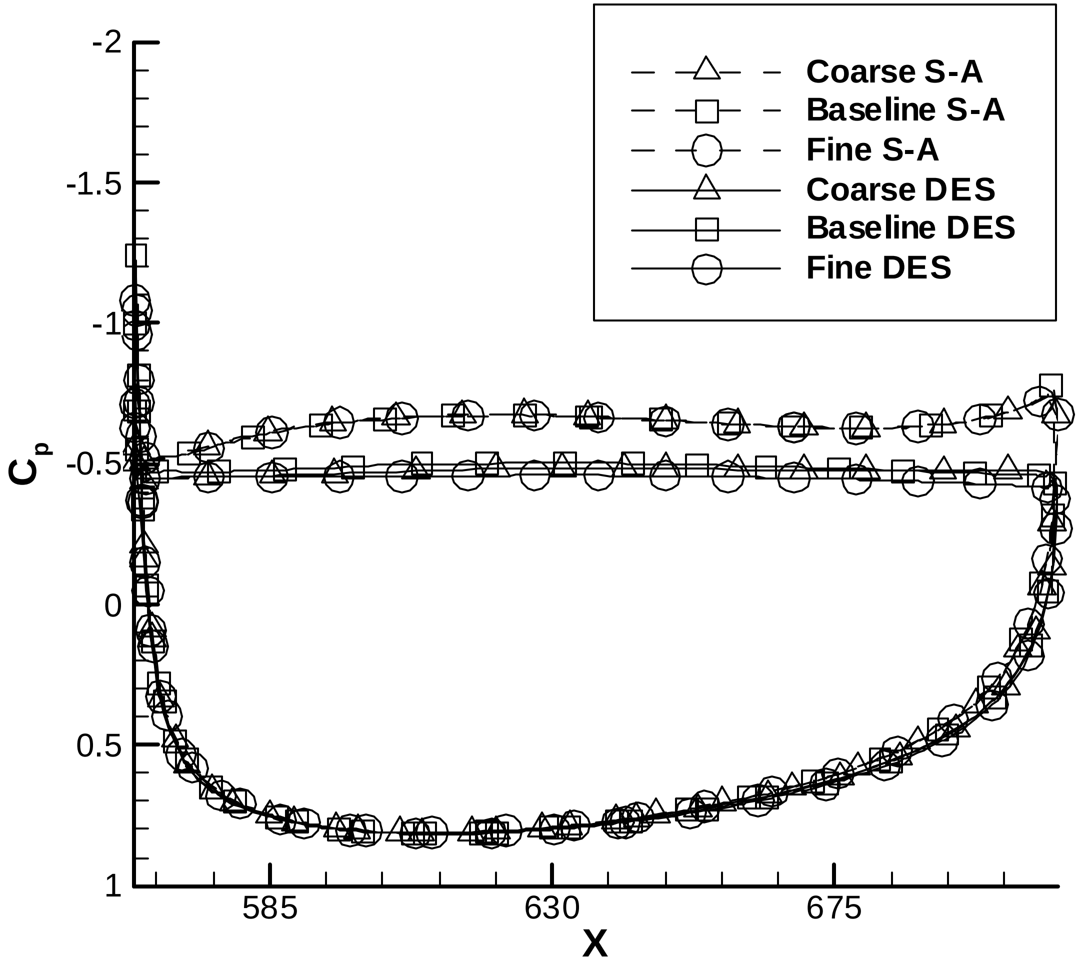
Grid Refinement





Time Averaged Pressures



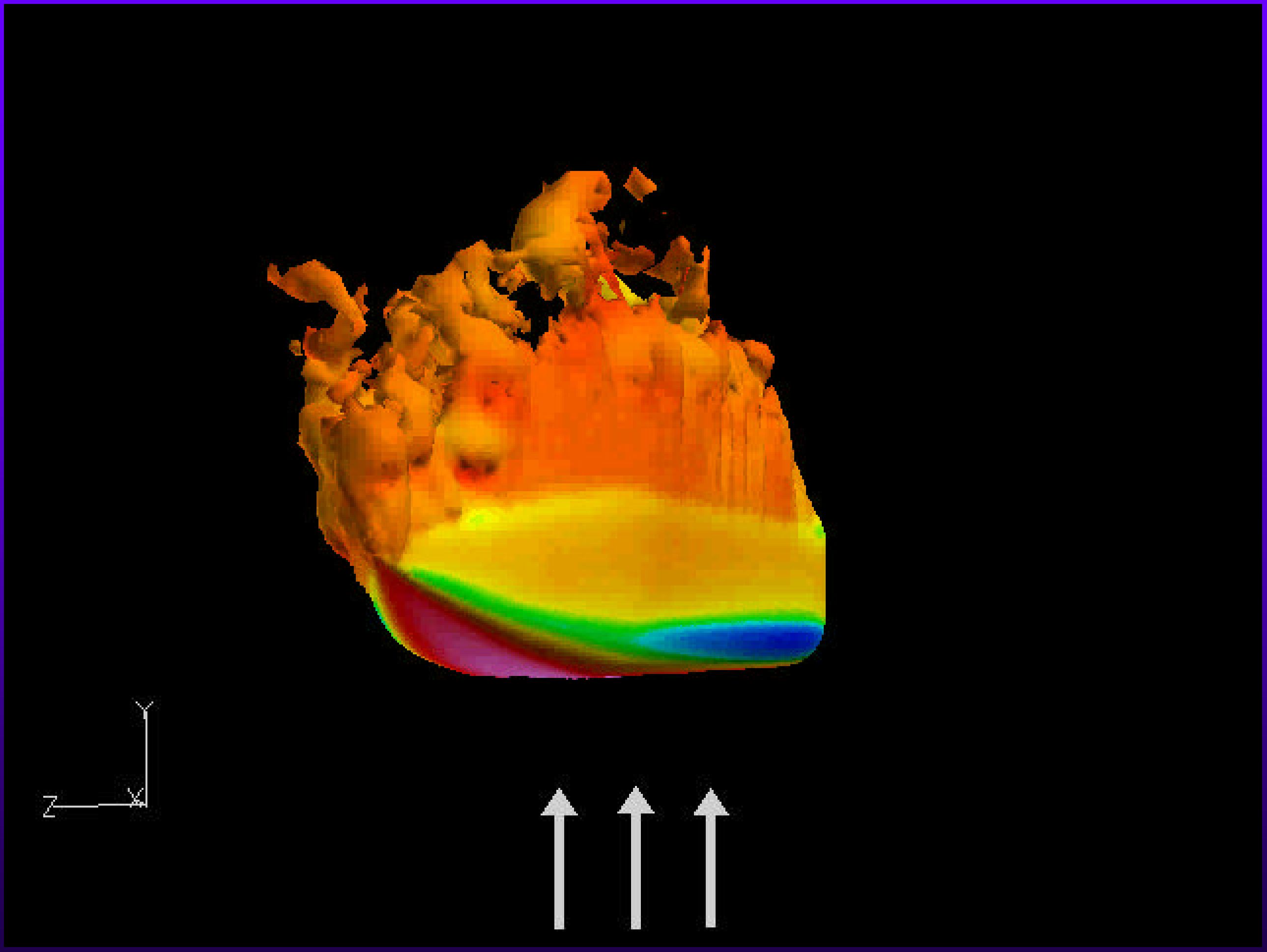


Integrated Forces

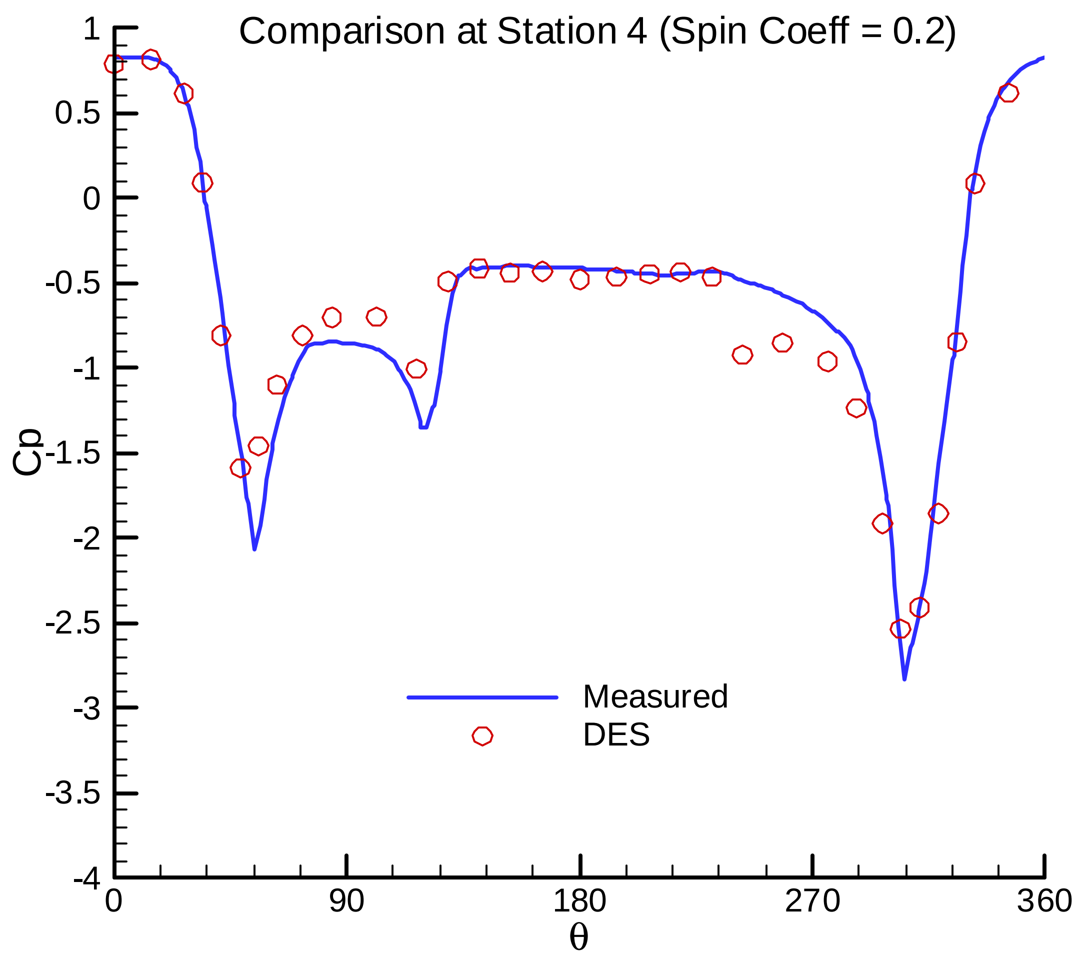
		C_L	C_D	C_M	$\%C_L$	$\%C_D$	$\%C_M$
	Exp	0.781	1.744	-0.466			
	Coarse	0.747	1.677	-0.431	-4.25%	3.86%	-7.62%
DES	Baseline	0.736	1.616	-0.495	-5.70%	-7.35%	6.10%
	Fine	0.759	1.648	-0.457	-2.81%	-5.52%	-2.00%
	Coarse	0.855	1.879	-0.504	9.49%	7.73%	8.17%
S-A	Baseline	0.852	1.867	-0.523	9.09%	7.05%	12.22%
	Fine	0.860	1.880	-0.507	10.22%	7.78%	8.72%

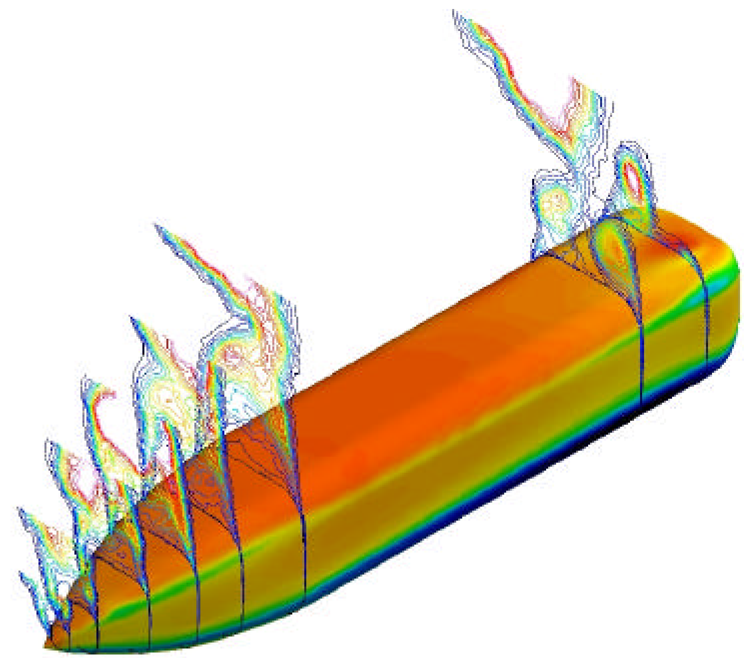
Forced Motion Validation of Detached Eddy Simulation

Isosurface of vorticity colored by pressure
Side and top views



Azimuthal Pressure Distribution, Wb/2V = 0.2





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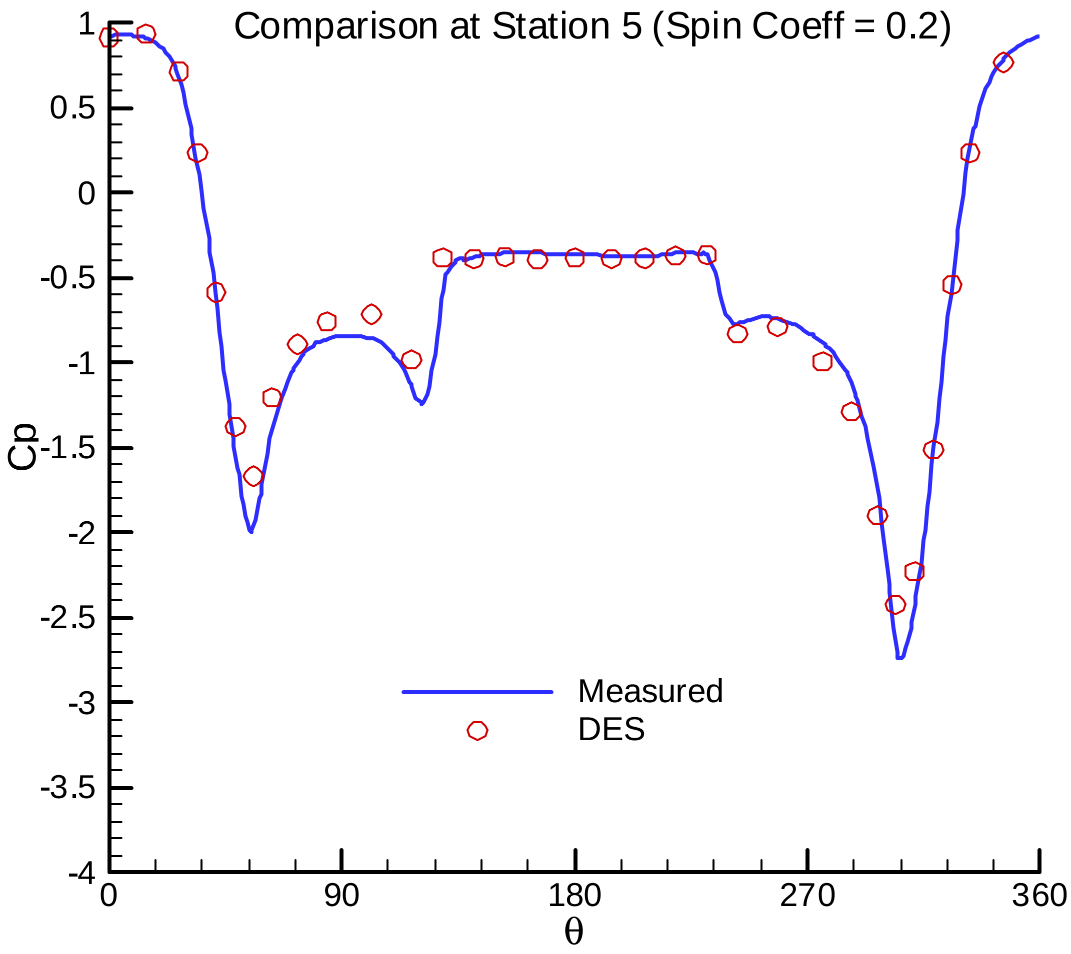
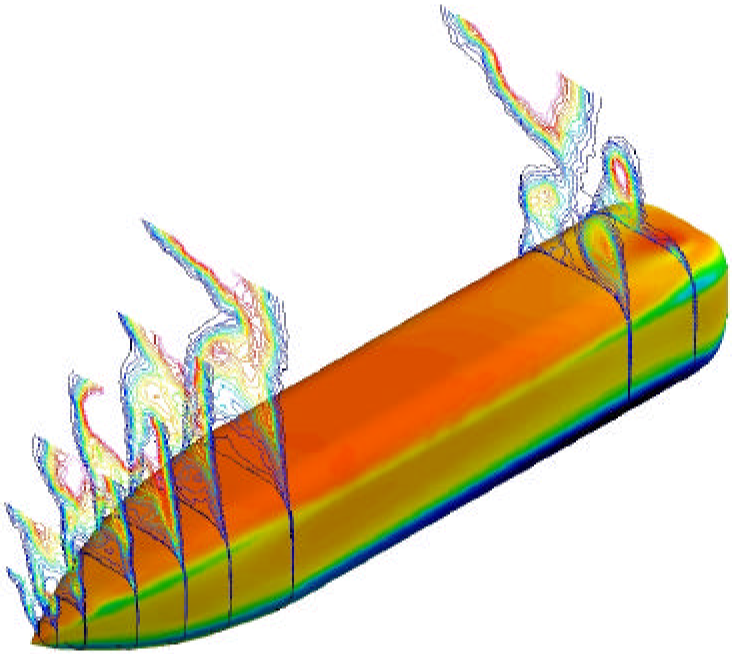


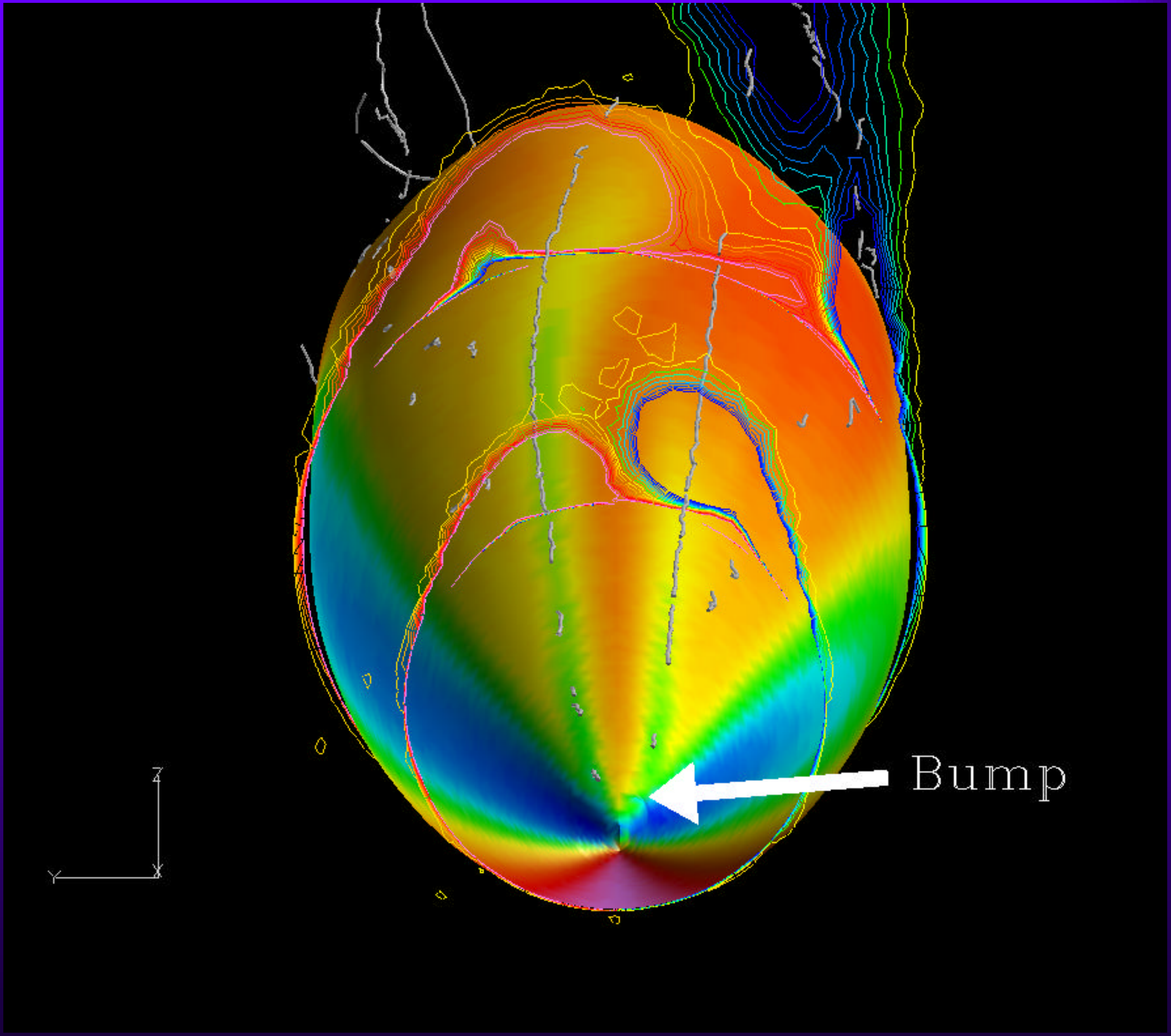


Preliminary Spin
F-15E at 65° angle of attack - DES

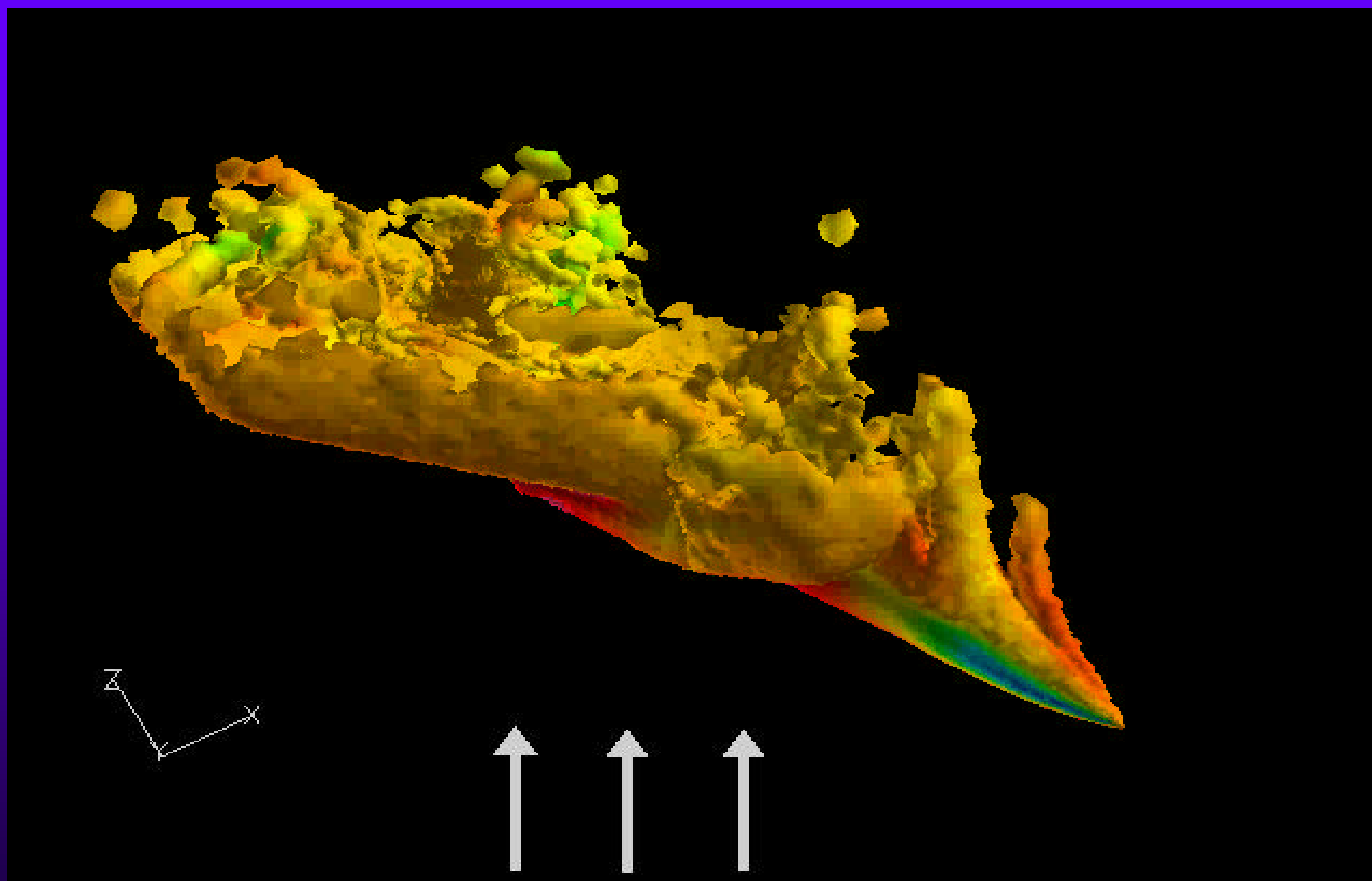
- grid (full aircraft): 6.46 x 10^6 cells (generated using VGRIDns)
  - prisms in the boundary layers, tetrahedra elsewhere
    - » conversion to prisms using *blacksmith*
  - average first $y^+ = 0.8$
  - Between resolution of coarse and baseline grids
- timestep = 0.02 (dimensionless using chord length and freestream speed)
- *Re* = 13.6 x 10^6, Mach number = 0.3
- rotary motion about centroid along freestream velocity vector

Asymmetric vortices (zero beta, no spin)

- Bump added to nose to reproduce strong yawing moment seen in flight test



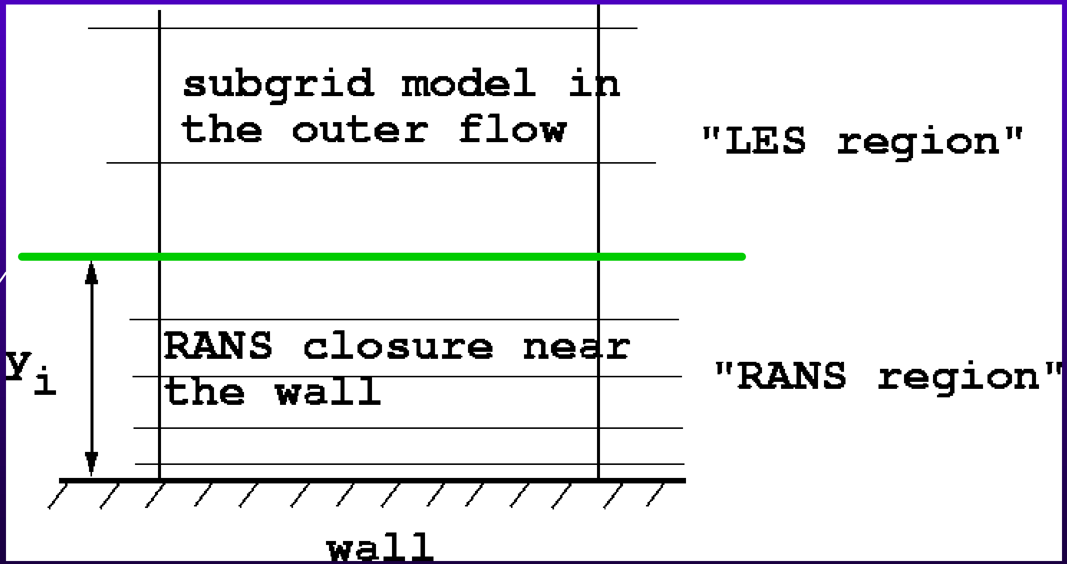
Vorticity isosurfaces, colored by pressure
Side and top views



Embedded LES Modifications to Detached Eddy Simulation

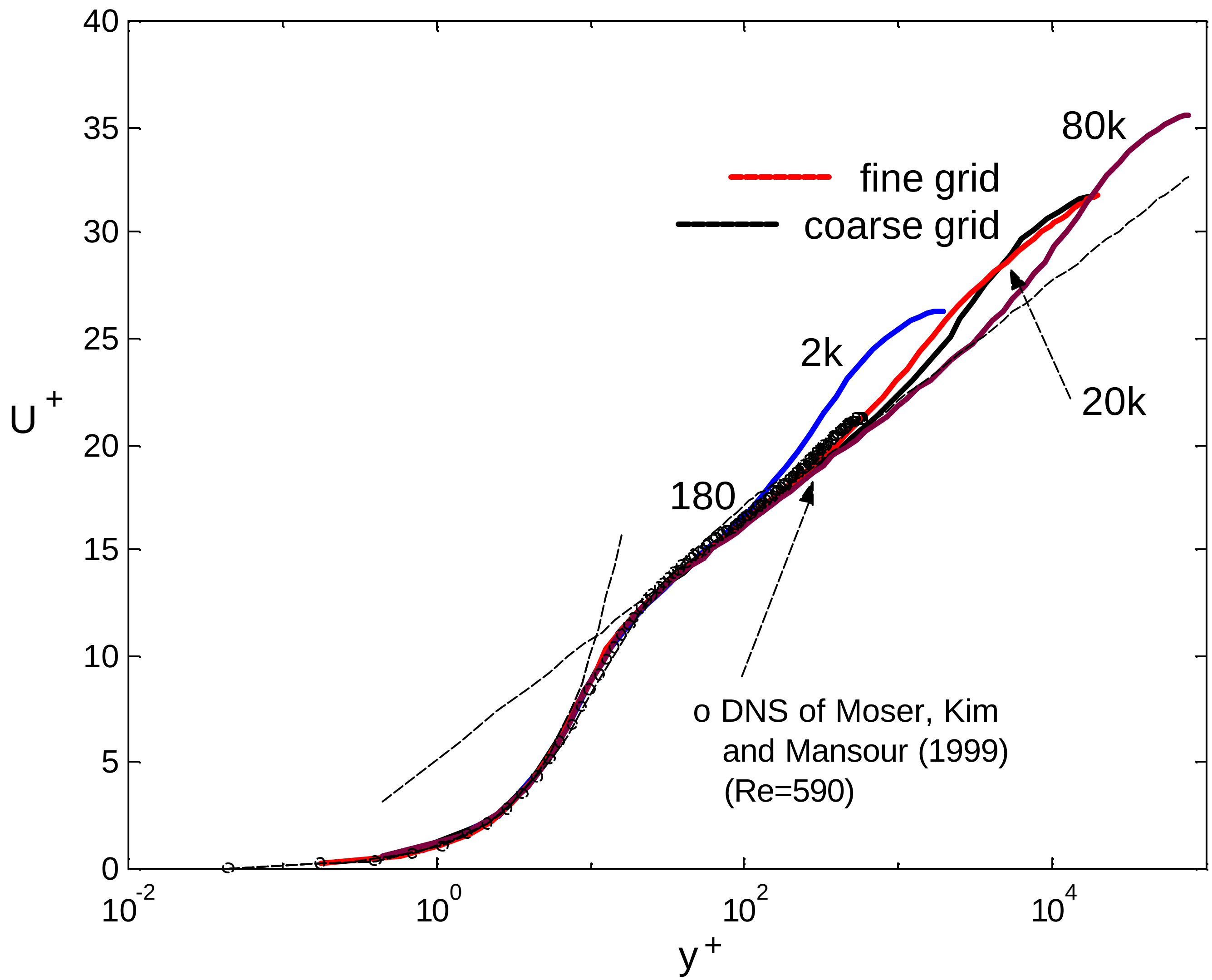
Research — embedded LES for turbulent channel flow

- importance of including "LES content" in the boundary layer prior to separation
  - flows with shallow separation
  - need grid densities sufficient to sustain eddy content near the wall
- another view of DES: LES with a complex wall-layer treatment



interface, y_i, between RANS and LES regions controlled by the grid

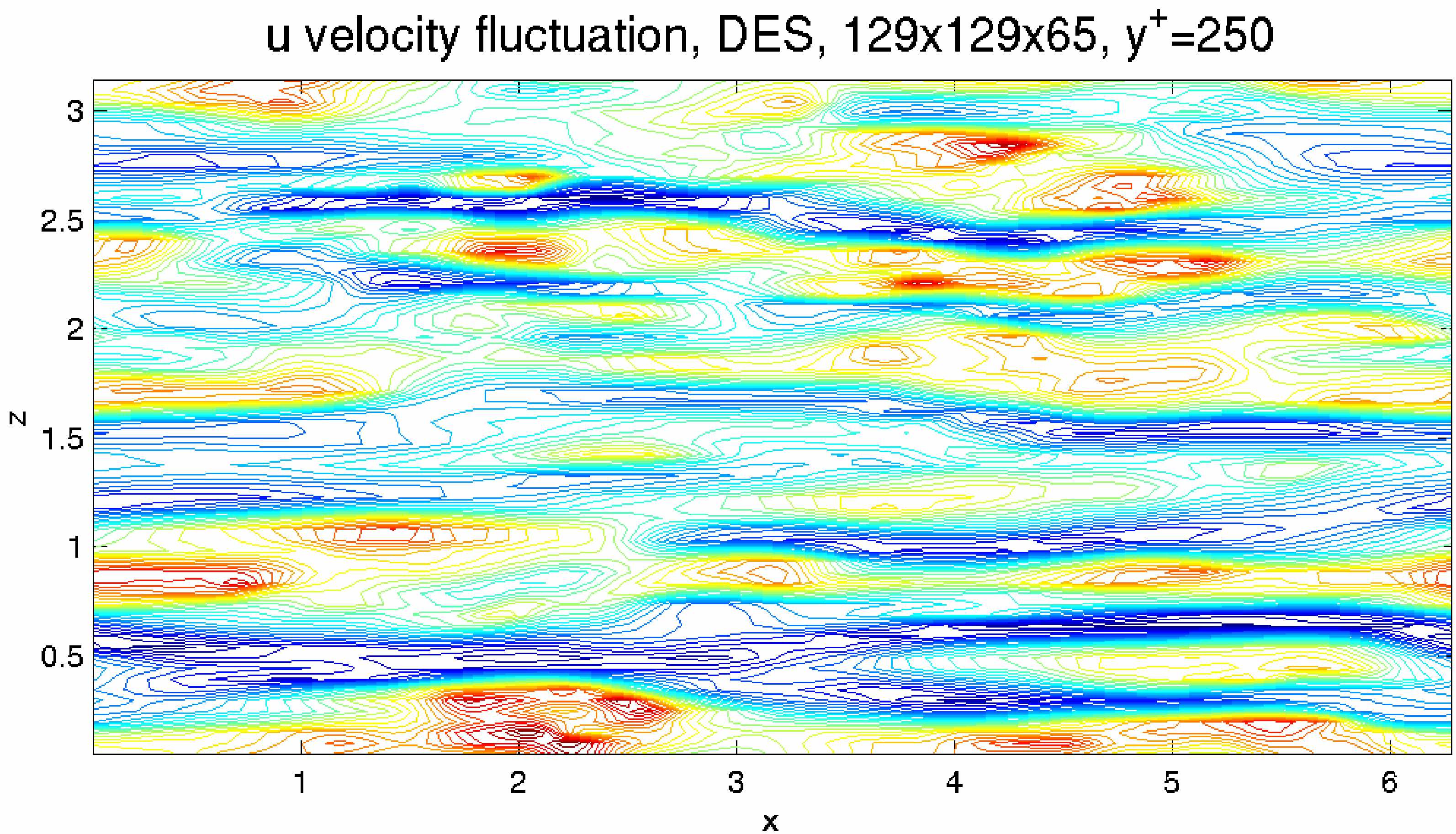
Mean Velocity



"super buffer" between RANS and LES velocity profiles

under-prediction of the skin friction (Nikitin et al. 2000)

Flow Structure near RANS-LES interface



$Re_t = 8000$

Backscatter

- **stochastically force the Navier-Stokes equations (Leith 1990, Mason and Thompson 1993, Carati *et al*. 1994…)**

$$\frac{Du_i}{Dt} = -\frac{1}{r}\frac{\partial p}{\partial x_i} + u\frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial t_{ij}}{\partial x_j} + f_i$$

$f_i =$ stochastic force distributed about RANS-LES interface

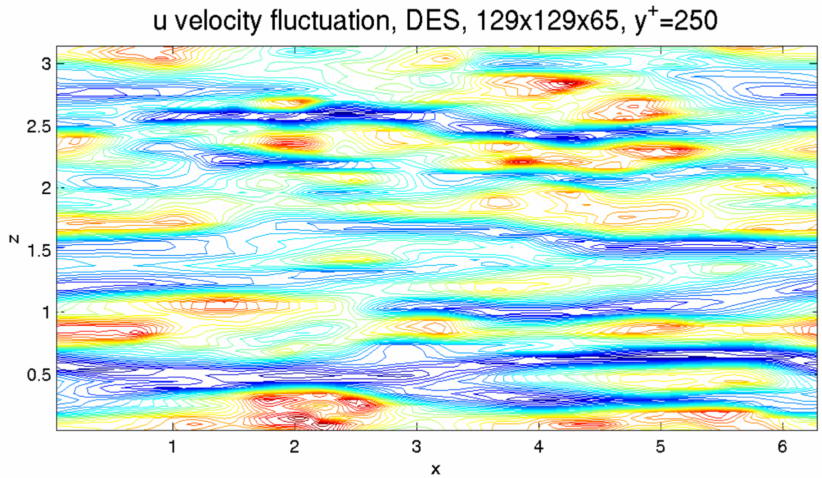
  - **purely random or scaling using the eddy viscosity, strain rate, and timestep**

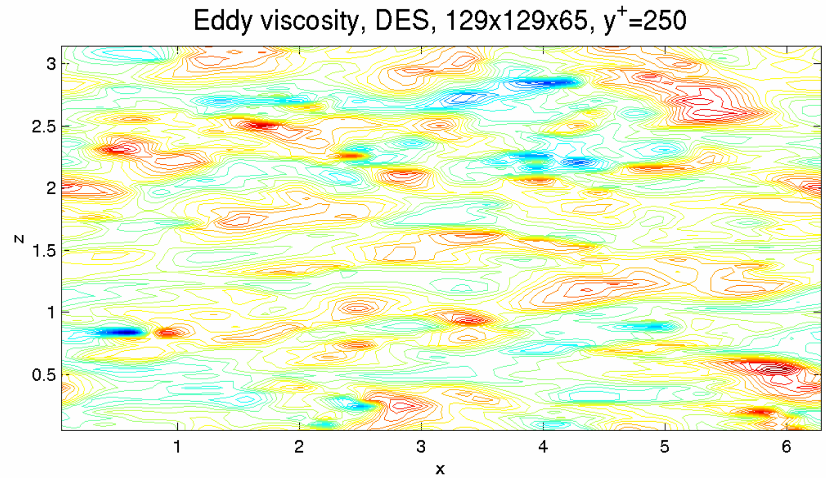
- **envelope over which force distributed**

$$e(y; l) = \frac{(l\, y)^2}{1 + (l\, y)^4}$$

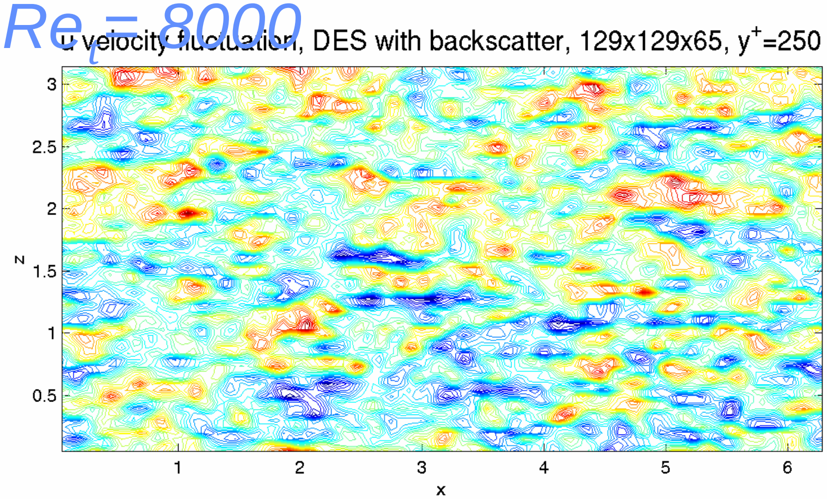
l adjusted so that maximum in envelope at RANS-LES interface

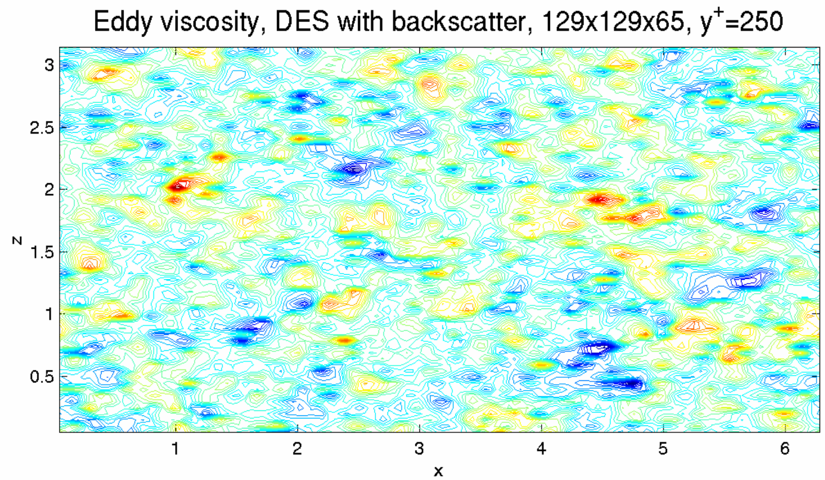
Flow Structure near RANS-LES interface



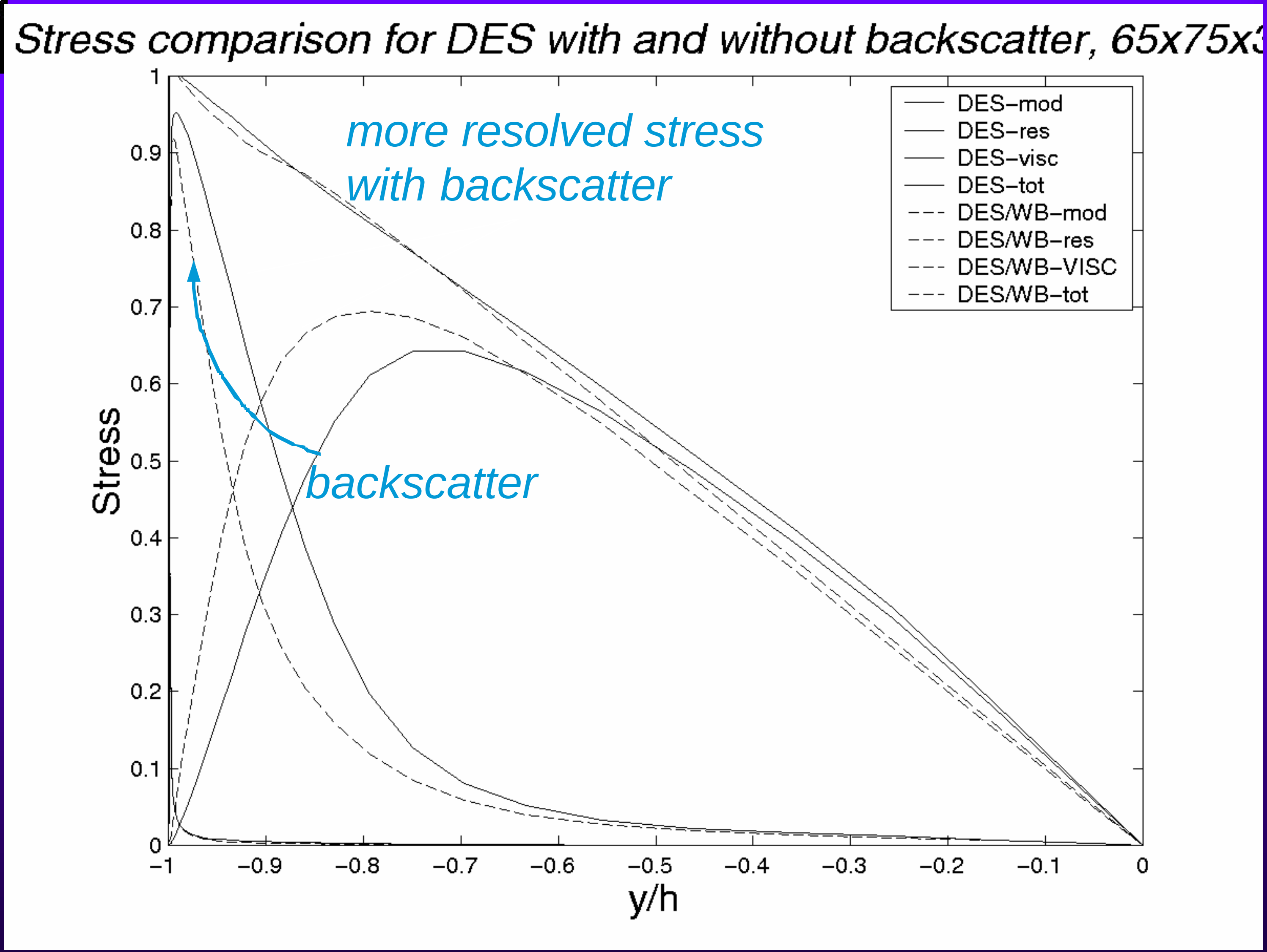


$Re_\tau = 8000$



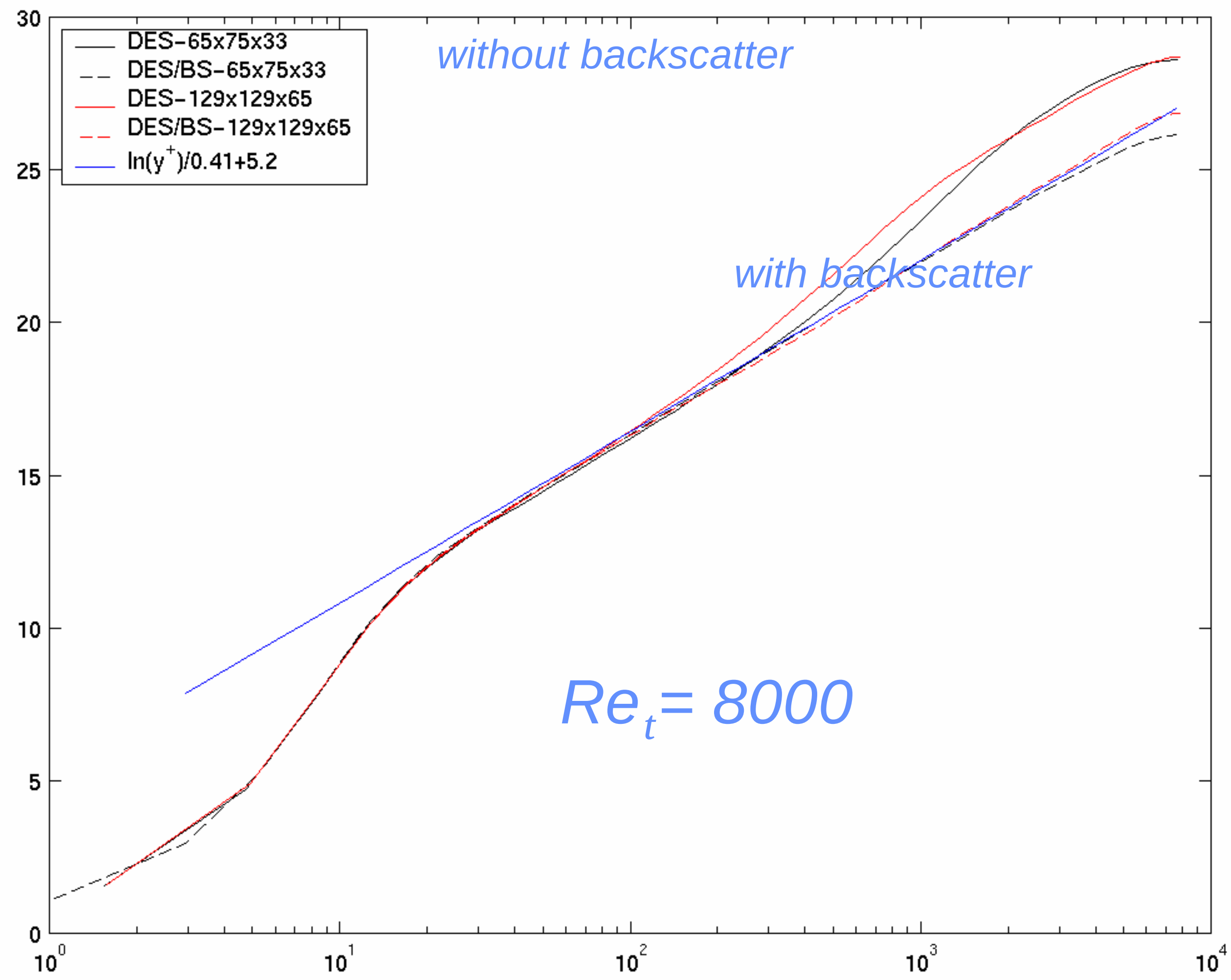


Turbulent Stresses



stochastic forcing raises resolved stress, lowers modeled stress

Mean Velocity



Future Areas of Research Necessary

- **Embedded LES to improve simulation of instabilities generated inside the boundary layer**
  - Need to continue the research outlined above
  - Apply the method to more test cases
- **Unsteady experiments of-**
  - Static high alpha UCAV configurations
  - Pitch and roll maneuver tests with unsteady data gathered
  - Possibly adopt the Boeing 1301 or 1303 as a standard configuration for several groups to test
  - High accuracy methods applied such as PIV, LDV, etc.

Conclusions

- **DES has been examined on a wide range of massively separated flows**
  - Moderate to greatly increased accuracy over traditional methods
  - Capability to predict unsteady flows at flight Re
    - Crucial for high alpha maneuvering
    - Crucial for aero-elasticity, aero-acoustics
  - Enough confidence built to encourage engineering use
- **Several areas of research needed to apply to super-maneuvering UCAVs with confidence**